Design Equation for CFRP strengthened Cold Formed Steel Channel Column Sections

Sreedhar Kalavagunta , Sivakumar Naganathan, and Kamal Nasharuddin Bin Mustapha
Universiti Tenaga Nasional,
Jalan IKRAM-UNITEN, 43000,
Department of Civil Engineering,
Kajang, Selangor, Malaysia.

Abstract* — Carbon fiber reinforce polymer (CFRP) strengthened steel structural members such as beams, columns and bridge decks have become progressively popular as a result of extensive studies in this field. This paper presents the recent developments in CFRP strengthened steel channel sections and proposed conceptual model for prediction of column strength under pure axial loads per Indian standards-IS801-1975 and Euro code 3(EC 3)standards . Eight cold-formed steel circular lipped channel section columns with externally bonded CFRP were tested under pure axial compression. IS801/EC3 proposed methods were compared with experimental results. The results show that the proposed method gives around 11 percent increase in strength due to CFRP.

Keywords- CFRP strengthening, IS801, Cold formed Steel , Axial Compression.

I. INTRODU CTION

Cold formed steel sections gained special attention in research due to its major advantages like flexibility in drawing up any shape, high ratio of strength to weight, light in weight, easy to transport and erect, recycle etc. Cold formed steel sections with edge stiffened flanges have three types of buckling like local buckling, distortional buckling, and Euler's buckling (flexural or flexural-torsional) generally called as global buckling, has been investigated by a number of researchers[1,2,3,4,5,6,7,8,9,10].

In recent years, the use of carbon fiber-reinforced polymer (CFRP) materials for repair strengthening and repair in columns has been widely utilized as a result of design code revision, environmental deterioration, physical aging, and catastrophic events.

Advantages of CFRP over other conventional repair materials include its higher strength to-weight ratio, additional corrosion resistance, very low coefficient of thermal expansion, and ease of application. Past two decades there are two major strengthening techniques have been widely applied, including CFRP plate bonding and column wrapping. In recent years, there has been a trend towards using this technique to repair and strengthen steel members with CFRP[11,12,13], particularly in the field of thin-walled steel structures.

CFRP wrapping method is an economical and easy-to-implement retrofitting method to

- Increase the axial compression.
- Increase shear strength
- Increase the flexural rigidity
- Increase the durability
- Increase seismic resistance etc,.

Most recently research on the strengthening on circular steel sections with CFRP, Jimmy Haedir et al., studied on axial compression and flexural and posed design equation for steel tubular sections[14,15,16,17], M. Elchalakani et al., on plastic mechanism [18], Nuno Silvestre et al., [19, 20] studied on non-linear behavior and load carrying capacity of CFRP-strengthened lipped channel steel columns.

II. MATERIALS AND METHODS

A Total of 8 CFRP strengthened cold formed channel sections and plain cold formed sections were tested. Each specimen was cut to final length, ranging from 500 mm to

700 mm and cross sectional dimensions are shown in Table 1.The steel used had a mean yield stress of 550 N/mm2, and modulus of elasticity 205000 N/mm2. Unidirectional high-strength carbon fibre sheets (Fig.
e 1) namely MBrace CF 130 of 3790 MPa ultimate tensile strength 230Gpa elastic modulus with a thickness of 0.176 mm were used in this investigation.

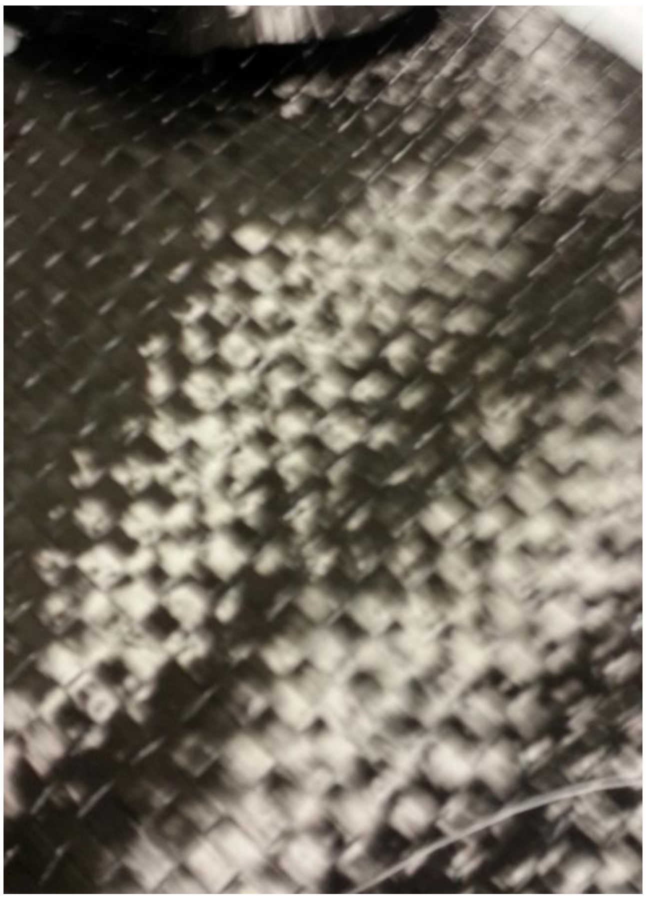

Figure 1: Uni direction CFRP sheet

The surface of the steel was ground with an abrasive disc and then cleaned by solvent to obviate any contamination on the surface and to promote good adhesive. Carbon fibre sheet is prepared according to the required dimensions and mixed high-modulus epoxy adhesive MC-Bauchemie was smeared uniformly on the surface of the fibre sheet (Fig. 2). The composite sheet was then placed around the exposed external surface of the column web and gradually pressed along the fibre axis. Proper surface preparation is essential in ensuring good bond between steel and CFRP.

The perfect bond between steel and CFRP is key success for strength of CFRP strengthening steel. Number of researches has been conducted on the bond behaviour between steel and CFRP [21,22,23,24,25,26].

Figure 2: Surface preparation

TABLE 1: *Section Dimensions and Properties*

Section Mm	Thickness mm	Yield stress Mpa	Area mm^2	Rx mm	Ry mm
C7510	1	550	137	29.84	12.67
C7512	1.2	550	204	30.43	15.96

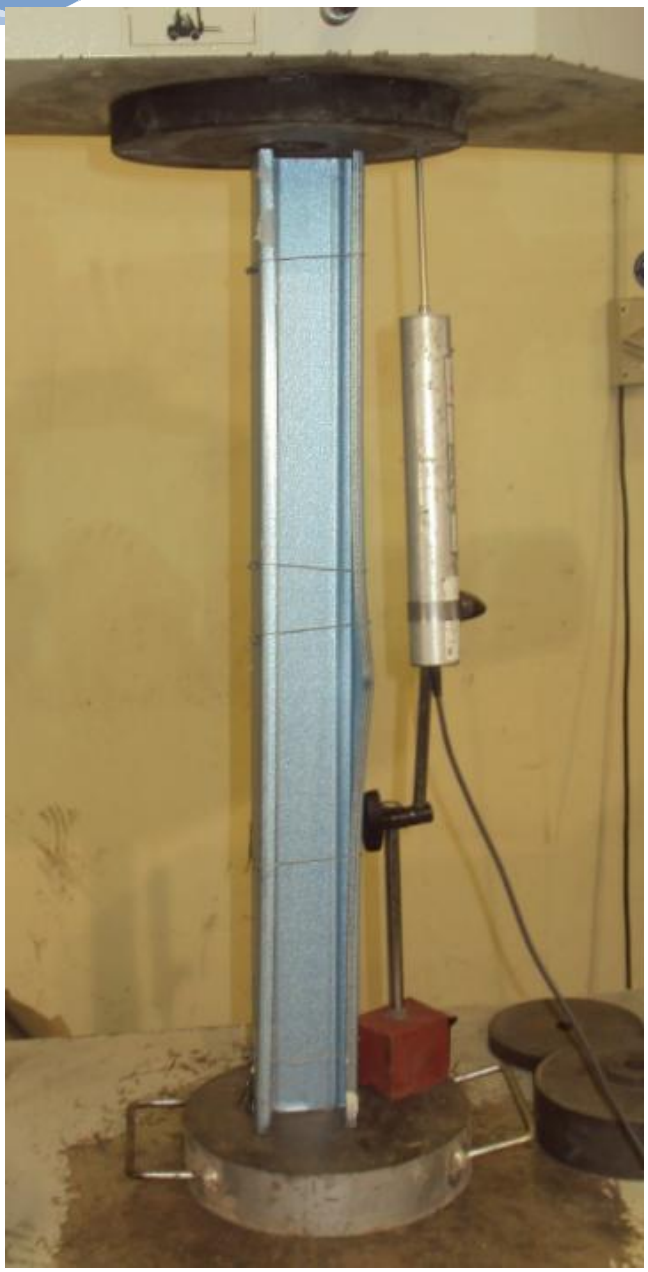

Figure 3: Test setup

The axial compression capacity were performed in a standard hydraulically testing machine (Fig.3) under low loading rate to allow full development of the various buckling/failure modes such as local buckling, distortional buckling, flexural - Torsional flexural buckling and to examine progression of the CFRP strengthened channel column. The experimental results for both plain and CFRP strengthened sections are shown in Table 6.

III RESULTS AND DISCUSSION

Cold formed steel sections are widely used in the construction industry due to their strength to weight ration and aesthetics. There have been studies on further strengthening with externally reinforced CFRP by various authors [4,27,28,29] . In this paper, design method proposed for CFRP strengthened cold-formed steel channel columns to estimate axial compression capacity under pure axial loads per Indian Standard IS801-1975[30]. The results are compared with experimental results as given in Table 6. Initially plain cold formed steel sections is tested under pure axial compression load and ultimate load results are given in Table 2.

TABLE 2: Ultimate Load of plain cold formed sections: Experimental

Section	FY Mpa	Ultimate Load - kN
C7510x500mm	550	57.97
C7510x600mm	550	57.88
C7510x700mm	550	56.75
C7512x500mm	550	72.65
C7512x600mm	550	71.08
C7512x700mm	550	69.5

Total thickness of CFRP layered plate (tt) considered as CFRP thickness (tcf) + steel plate (ts) neglecting adhesive layer thickness (as this is weak in strength and buckling) given by (1). The elastic modulus of the CFRP with steel is determined by the modular ratio concept and given by Eq. (2).The modified allowable axial stress based on section 6.6.1.1-IS801-1975 given by (3) and (4).

The ultimate load determined based on (5), results are shown in Table 3.

$$t_t = (t_{cf}) + t_s \quad (1)$$

$$E_{cfrp} = \frac{E_s t_s + E_{cf} t_{cf}}{t_s + t_{cf}} \quad (2)$$

The allowable compressive strength for pure axial compressed member is given by IS801-1975 and is modified to account CFRP effect. The CFRP thickness is considered for calculating Euler buckling stress.

The modified allowable axial compression stress of composite section

$$KL/r \ < \frac{C_e}{\sqrt{Q}}$$

$$F_{al\_cfrp1} = \frac{12}{23} QF_{ry} - \frac{3(QF_r)^2}{23 \Pi^2 E_{cfrp}} \left(\frac{KL}{r}\right)^2 \quad (3)$$

$$KL/r \ \geq \frac{C_e}{\sqrt{Q}}$$

$$F_{al\_cfrp1} \ = \frac{12 \Pi^2 E_{cfrp}}{23(KL/r)^2} \quad (4)$$

Section 6.6.1.2 - IS801-1975 also considered as lipped channels are singly symmetric open cross sections.

$$\sigma_{TFO} > 0.5 \ F_y$$

$$F_{al\_cfrp2} \ = 0.522 F_y - \frac{F_y^2}{7.67 \sigma_{TFO}}$$

$$\sigma_{TFO} \leq 0.5 \ F_y$$

$$F_{al\_cfrp2} \ = 0.522 F_y$$

$$P_{u\_allowable} = A_{eff} \, F_{al\_cfrp} \quad (5)$$

$$P_{u\_all} = (A_{seff} + A_{cfrp}) \, F_y \quad (6)$$

Where

Q is the ratio between Effective design area / Gross sectional design area calculated,

Ce is $\sqrt{2\pi^2 E_{cfrp}/f_y}$, Fy is the yield strength Steel member alone,

$$\sigma_{TFO} = \frac{1}{2\beta} \left[(\sigma_{ex} + \sigma_t) - \sqrt{(\sigma_{ex} - \sigma_t)^2 - 4\beta \sigma_{ex} \sigma_t} \right]$$

Other parameters, as described in section 6.6.1.2 IS801-1974.

However, theoretical ultimate load is calculated based on yield stress multiplied with effective cross sectional area.

The proposed method results in table 3 clearly show good agreement with experimental results.

TABLE 3 CFRP Strengthened cold formed steel members as per IS801-1974

Section	Ultimate Load-CFRP-Steel -Experimental-kN	Ultimate Load-CFRP-Steel -Theoretical-kN
C7510x500mm	64.26	65.07
C7510x600mm	64.01	64.86
C7510x700mm	64.05	64.59
C7512x500mm	80.05	84.14
C7512x600mm	79.64	83.56
C7512x700mm	78.92	83.25

The design equations are also developed based on Eurocode3 1993-1-3:2001: Design of steel structures to validate experimental results. The equivalent elastic modulus is calculated based on static modular ratio principles. The modified equations illustrate the proposed design approach to find ultimate axial compression load.

$$N_b = \chi A_{eff} f_y / \gamma_{M1} \quad (6)$$

$$N_b = \chi \beta_A A_g f_y / \gamma_{M1} \quad (7)$$

$$\beta_A = A_{ef} / A_g \quad (8)$$

$$\chi = \frac{1}{\emptyset + [\emptyset^2 - \bar{\lambda}^2]} \leq 1.0 \quad (9)$$

$$\phi = 0.5 \left[1 + \alpha(\bar{\lambda} - 0.2) + \bar{\lambda}^2 \right] \quad (10)$$

$\bar{\lambda}$ is the relative slenderness for the relevant buckling mode

$$\bar{\lambda} = (\lambda/\lambda_1)[\beta_A]^{0.5}$$

λ= length / least radius of gyration

$$\lambda_1 = \pi [E/fy]^{0.5}$$

α is and imperfection factor, depending on the appropriate buckling curve. Table 6.1 in Euro code 3: 1993-1-3

A_{eff} is the effective area of the cross section,

A_g is the area o the gross cross section

χ is the appropriate value of the reduction factor for buckling resistance.

γ_{M1} is the design factor considered as unity .

The members summarized in table 1are studied based on Euro code 3 standards to determine ultimate load strength and the results are given in Table 4. The ultimate load strength results are in good agreement with proposed design methods based on Eurocode3 1993-1-3:2001.

TABLE 4 CFRP Strengthened cold formed steel members as/Euro code

Section	Ultimate Load-CFRP-Steel - Experimental-kN	Ultimate Load-CFRP-Steel - Theoretical-kN
C7510x500mm	64.26	64.10
C7510x600mm	64.01	62.96
C7510x700mm	64.05	61.79
C7512x500mm	80.05	80.10
C7512x600mm	79.64	78.82
C7512x700mm	78.92	77.52

TABLE 5 Ultimate load for CFRP Strengthened cold formed steel members IS801 vs. Euro code

Section	IS801-Kn	Eurocode-kN
C7510x500mm	65.07	64.10
C7510x600mm	64.86	62.96
C7510x700mm	64.59	61.79
C7512x500mm	84.14	80.10
C7512x600mm	83.56	78.82
C7512x700mm	83.25	77.52

This Table 5 presents a proposed design method of IS801 and Euro code 3.

The results indicate that proposed design methods of both the codes are achieved at same level of reliability.

The experimental results of plain and CFRP strengthen are provided in Table 6. The result shows that capacity of CFRP strengthened beams is dominated by strength. It should be noted that the increase in strength due to CFRP is around 11%.

TABLE 6 Axial Compression tests results of CFRP Strengthened cold formed steel members vs. Plain Cold formed steel

Section	Ultimate Load-Plain-Steel - Experimental-kN	Ultimate Load-CFRP-Steel - Experimental-kN	% of increase in strength due to CFRP.
C7510x500mm	57.97	64.26	10.85
C7510x600mm	57.88	64.01	10.59
C7510x700mm	56.75	64.05	12.86
C7512x500mm	72.65	80.05	10.18
C7512x600mm	71.08	79.64	12.042
C7512x700mm	69.5	78.92	13.55
Average Increase of CFRP Strength			11.681

Figure 3: Failure mode: Bond failure

The modes of failure in Fig. 3 demonstrated that the CFRP strengthened cold formed steel sections is generally developed by the same plastic mechanism in mode of failure when compared with plain cold formed steel sections. In addition CFRP strengthened members are failing due to

- Bond failure (debonding)
- Surface failure (delaminating)

Figure 4: Failure mode: Local failure

IV. Concluding Remarks:

The proposed design guidelines included CFRP to account slenderness effects to determine the axial compression capacity of CFRP strengthened steel columns. The proposed design rules based on IS801 and Eurocode were validated through a comparative study with experimental test results. The experiment results shows that the capacity of CFRP strengthened lipped channel sections were up to 11% greater than plain steel columns.

However, further research required on areas like surface preparation, CFRP with different layers, adhesive materials and guide lines of CFRP wrapping to validate the proposed equations.

References:

1. M.Macdonald, M.A Heiyantuduwa, J.Rohodes. Recent development in the design of cold-formed steel members. Thin-Walled Structures. 46(2008) 1047-1053.
2. Poologanathan Keerthan , Mahen Mahendran. New design rules for the shear strength of LiteSteel beams . Journal of Construction Steel Research 67(2011) 1050-1063.
3. Alireza Bagheri Sabbagh, Mihail Pekovski. Ductile moment-resisting frames using cold-formed steel sections: An analytical investigation. Journal of Constructional Steel Research 67(2011) 634-646.
4. **Nabil Abdel-Rahman and K. S. Sivakumaran (1998)** Effective design width for perforated cold-formed steel compression members, Canadian Journal 25(2): 319-330.
5. Eduardo de Miranda Batista. Local-global buckling interaction procedures for the design of cold-formed columns: Effective width and direct method integrated approach. Think – Walled Structures 2009: (47) 1218-1231.
6. Thanuja and Mahen Mahendran. Numerical modeling of light gauge cold-formed steel compression members subjected to distortional buckling at elevated temperatures. Think-Walled Structures 48(2010) 334-344.
7. P. Borges Dinis, Dinar Camotim. Local/distortional mode interaction in cold-formed steel lipped channel beams. Thin-Walled Structures 48(2010) 771-785.
8. SputoT, TovarJ. Application of Direct Strength Method to axially loaded perforated cold-formed steel studs: Long wave buckling. Thin-Walled Structures 2005;43(12):1852–81.
9. Crisopher D.Moen, B.W.Schafer. Elastic buckling of cold-formed steel columns and beams with holes, Engineering Structures. 31(2009) 2812-2824.
10. K. Velchev,G.Comeau,N.Balh,C.A.Rogers. Evaluation of the AISI S213 seismic design procedures through testing of strap braced cold-formed steel walls, Think – Walled Structures 2010: (48) 846-8565-3 2005, Revision 2006.
11. Reza Haghani , Mohammad Al-Emrani, A new design model for adhesive joints used to bond FRP laminates to steel beams – Part A: Background and theory. Construction and Building Materials 34 (2012) 486–493.
12. Zhao XL, Zhang L, State of the art review on FRP strengthened steel structures. Eng Struct 2007;29(8):1808–23.
13. Amr Shaat, Amir Z.Fam, Slender Steel Columns Strengthened Using High-Modulus CFRP Plates for Buckling Control. *J. Compos. Constr.*, Volume 13, Issue 1 (February 2009), p. 2–12.
14. Haedir, J.; Zhao, X.L, Design of short CFRP-reinforced steel tubular columns. *Journal of Constructional Steel Research*, Volume 67, issue 3 (March, 2011), p. 497-509.
15. J. Haedir , X.-L. Zhao , M.R. Bambach , R.H. Grzebieta. Analysis of CFRP externally-reinforced steel CHS tubular beams. Composite Structures 92 (2010) 2992–3001.
16. Haedir J, Bambach MR, Zhao X-L, Grzebieta RH. Strength of circular hollow sections (CHS) tubular beams externally reinforced by carbon FRP sheets in pure bending. Thin-Walled Struct 2009;47(10):1136–47.
17. Jimmy Haedir , Xiao-LingZhaon, Raphael H.Grzebieta , Michael R.Bambach. Non-linear analysis to predict the moment–curvature response of CFRP-strengthened steel CHS tubular beams. Thin-Walled Structures 49 (2011) 997–1006 .
18. M. Elchalakani, M.R.Bambach. Plastic mechanism analysis of CHS stub columns strengthened using CFRP. *Electronic Journal of Structural Engineering, 7(2007)*
19. Nuno Silvestre, Ben Young, Dinar Camotim, Non-linear behaviour and load-carrying capacity of CFRP-strengthened lipped channel steel columns. Engineering Structures 30 (2008) 2613–2630
20. NunoSilvestre , DinarCamotim , BenYoung, On the use of the EC3 and AISI specifications to estimate the ultimate load of CFRP-strengthened cold-formed steel lipped channel columns, Thin-Walled Structures 47 (2009) 1102–1111
21. Xia S., Teng J. Behaviour of FRP-to-Steel Bonded Joints. Proceedings of the International Symposium on Bond Behaviour of FRP in Structures (BBFS),Hong Kong,December, 2005. p. 419-26.
22. Fawzia S, Al-Mahaidi R, Zhao XL. Experimental and finite element analysis of a double strap joint between steel plates and normal modulus CFRP. Composite Structures. 2006;75:156-62.
23. Liu HB, Zhao XL, Al-Mahaidi R. Effect of fatigue loading on bond strength between CFRP sheets and steel plates. International Journal of Structural Stability and Dynamics. 2010;10:1-20.
24. Challita G, Othman R, Casari P, Khalil K. Experimental investigation of the shear dynamic behavior of double-lap adhesively bonded joints on a wide range of strain rates. International Journal of Adhesion and Adhesives. 2011;31:146-53.
25. Chao Wu, XiaolingZhao , WenHuiDuan , RiadhAl-Mahaidi, Bond characteristics between ultra high modulus CFRP laminates and steel, Thin-Walled Structures 51 (2012) 147–157
26. Teng JG, Zhang LF. Finite element predictions of interfacial stresses in beams bonded with a thin plate. In: Proceedings of the international symposium on bond behaviour of FRP in structures, Hong Kong, China; 2005. 16
27. Haedir J. and Zhao, X.L. (2012), Design of CFRP-strengthened steel CHS tubular beams, Journal of Constructional Steel Research, 72(5), 203-218
28. Fawzia, S., Al-Mahaidi, R., Zhao, X.L. and Rizkalla, S. (2007), Investigation into bond between CFRP and Steel Tubes, Construction and Building Materials, 21(4), 839-847
29. Teng JG, Hu YM. Behaviour of FRP-jacketed circular steel tubes and cylindrical shells under axial compression. Construction and Building Materials 2007 21(4):827–38.
30. Indian code IS800-2007. General Construction in Steel - Code of practice . Bureau of Indian Standards, New Delhi.
31. Eurocode 3: Design of steel structures - Part1.3: General rules - Supplementary rules for cold formed thin gauge members and sheeting 1993-1-3:2001